Comparison of exposure to traffic-related pollutants on different commuting routes to a primary school in Jinan, China

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Abstract

Traffic-related pollutants seriously affect human health, and the commute time to and from school is the time when students are exposed greatest to traffic pollution sources. Field measurements were conducted with hand-held instruments while walking along two selected commuting routes in winter and spring. The measured data were then compared with background monitoring data, and the respiratory deposition dose (RDD) was calculated to assess the exposure risk. Particulate matter intake from 2018 to 2020 was calculated. In winter, the average concentrations of PM_{2.5} and PM₁₀ were higher in the afternoon than in the morning. The highest concentration was 2.94 times greater than the background value. The low-concentration distribution area of the low-traffic route that is off the main road (route B) was more significant than that of the high-traffic route that is near the main road (route A). Moreover, the RDD of route B was consistently lower than that of route A, while the average annual amount of PM_{2.5} inhalation on route B in 3 years was 16.3% lower than that on route A. Overall, route B is more suitable than route A for students to commute on foot. Based on the findings, a walking route located within a community is a good choice.

Keywords Traffic · Particulate matter concentration · Primary school · Commuting route · Spatial variation · Respiratory deposition dose

Introduction

With the continuous development of the economy and society, car ownership gradually increases (Dillman et al. 2021), which is accompanied by increases in the concentrations of traffic-related pollutants (Zheng et al. 2021). Exposure to traffic-related pollution affects the human respiratory system (Bai et al. 2018; Brugha and Grigg 2014) and the cognitive and developmental nervous system (Basagana et al. 2016; Sunyer et al. 2017) and may cause damage to other organs

and tissues of the human body (Bhaskaran et al. 2011; Pang et al. 2021; 2016; van Berlo et al. 2010). More severe cases of pollution exposure lead to increased mortality (Cui et al. 2020; Tang et al. 2020; Walker et al. 2019). Primary school students are at a developmental stage, and their body systems and organs are immature. Thus, if they are exposed to high levels of traffic pollution, they may suffer more damage than ordinary adults. The recurrence of respiratory diseases such as respiratory infection, pneumonia, asthma, tracheitis, and bronchitis within 1 year among children in severely polluted primary schools is higher than that in lightly polluted primary schools (Chen et al. 2019; Kim et al. 2013). The risk of asthma increases as the traffic-related pollution exposure increases near schools, with a hazard ratio (HR) of 1.45 and 95% confidence interval ranging from 1.06 to 1.98. In models with nitrogen dioxide and simulated traffic exposure, asthma was independently associated with traffic-related pollution in schools, and the effect of nitrogen dioxide was attenuated (HR = 1.37; 95% CI = 0.69–2.71) (McConnell et al. 2010). Moreover, in addition to health problems, exposure to high concentrations of traffic pollution can result in a decline in students' performance (Pastor

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et al. 2004; Rosofsky et al. 2014) and reduced attendance (Mohai et al. 2011). Therefore, attention should be paid to students' exposure to traffic pollution.

Many studies have investigated the concentrations of these pollutants both in and around schools (Brown et al. 2021; Kumar et al. 2020b; Sunyer et al. 2017; Wadlow et al. 2019), and many meaningful conclusions and mitigation measures have been determined (Dirks et al. 2016; He et al. 2020; Kumar et al. 2020a). While the research on traffic pollutants around schools is currently increasing, the research scope is relatively large, and most studies focus on the overall impact of traffic.

Vehicle exhaust and road dust are the main causes of the increases in concentrations of particulate matter (Harrison et al. 2021). Traffic-related pollutants have limited distribution distances due to obstruction from buildings and trees, as well as interference from airflow (Ozdemir 2019). The commuting period is the time during which students are most directly exposed to automobile exhaust. Compared with other daily activities, students are closer to vehicles, directly exposed to traffic-related pollutants, and have a higher exposure time ratio, especially in traffic hot spots (Buonanno et al. 2013; Dons et al. 2011; Rivas et al. 2016). Moreover, school times coincide with the morning rush hour, and signalized traffic intersections will have particularly high concentrations of particulate matter due to delays and stops of road vehicles, increasing the risk of exposure (Goel and Kumar 2015). Different modes of commuting and different commuting routes can cause people to inhale different concentrations of pollutants (Ahmed et al. 2020; Karageorgou et al. 2021; Qiu et al. 2017).

The state of urban pollution is monitored by uniformly arranged air quality monitoring stations, the location and monitoring range of which are fixed and limited. Generally, monitoring stations are located far from school areas, so they cannot represent the pollutant concentration around schools and on commuter routes. It is especially difficult to promptly reflect the increase of pollution levels in local areas caused by urban traffic peaks or commuter transport peaks (Song et al. 2020; Tischer et al. 2019). This makes the assessment of students' exposure too optimistic, which can pose a greater health risk to students.

This study compares measured data with background data to analyze the gap between them and ultimately provide support for the establishment of roadside traffic monitoring points. In this study, two different commuting routes were selected, one of which (route B) is away from the main road and the other of which (route A) is near the main road, to measure the concentrations of particulate matter during the commuting period. The respiratory deposition dose (RDD) of particulate matter was calculated, and the exposure of students during commuting was assessed. Furthermore, according to the ratio of the measured data to the background data,

the difference in the amount of particulate matter inhaled on fixed routes in 3 years was analyzed to prove the importance, and identify the factors, of route selection. The framework of this paper is shown in Fig. 1.

Literature review

Many studies have explored the pollution status of different routes or at different times. For instance, Garcia-Algar et al. (2014) tested the concentration of ultrafine particles (UFPs) on three different streets and distinguished the pollution at both infant height and adult height; the results showed that babies in strollers were exposed to higher levels of pollution than walking adults. Kumar et al. (2017) measured the pollutant concentration along a given route during commuting time, and it was found that the particulate matter concentration (PMC) and particulate matter number (PNC) to which infants were exposed were significantly increased during the peak period, especially at intersections and bus stops. Elford and Adams (2019) developed a pollutant dose model for commuting that combines the impacts of the commuting mode and topographic forced ventilation rate to predict pollutant concentrations on different routes and proposed the concept of low-dose routes. Mölter and Lindley (2015) analyzed the costs and benefits of fast routes and primary school walking routes with lower pollution exposure via a geographic information system (GIS); the results demonstrated that the relative degree of the reduction of pollution exposure is greater than the relative degree of the increase of the path length. Li et al. (2017) evaluated the pollution exposure on different routes and by different modes of transportation via real-time measurements; the mobile personal monitoring results indicate that motorcyclists are exposed to high levels of pollutants for short periods of time during commuting. The results of these studies effectively provide recommendations for the selection of commuting routes with less pollution to improve the health of citizens, and the specific research contents are summarized in Table 1.

Via the preceding literature review, it is evident that previous studies have involved the comparison of the pollutant concentrations of different routes and different modes of commuting, but there have been relatively few studies on student

groups. There are few practical methods for the measurement of pollutant concentrations on different student commuting routes, and most methods are model predictions. In many previous studies, the measurement time was chosen as the traffic rush hour, but this does not completely coincide with the school commuting time; the afternoon commute of primary school students is sometimes earlier than the evening rush hour. Therefore, based on these shortcomings, the present research focuses on students who are more

Fig. 1 The framework of this paper

vulnerable to traffic pollution. In addition, field measurements were carried out strictly according to the commuting time of students, and an exposure risk assessment was carried out to effectively provide suggestions for students' choice of commuting routes.

Methodology

Study area

The study was conducted in the No. 2 middle school attached to the Shandong Normal University (SDNU), Licheng District, Jinan, Shandong Province, China. Jinan is located in the central part of Shandong Province with a geographical location between 36°02'–37°54' N and 116°21'–117°93' E, as shown in Fig. 2a. It is located in the warm temperate continental monsoon climate zone and has four distinct seasons. The dominant wind direction is east in winter and changeable in spring. Jinan is also an important transportation hub; by the end of 2019, the number of motor vehicles in Jinan had reached 2.8533 million. During the study, particulate matter data were collected from the air quality monitoring site of Shandong Jianzhu University, which is the closest monitoring site to the study area. The linear distance.

of the monitoring site from the measurement origin is 1500 m, and the relative position is shown in Fig. 2b.

Route description

As presented in Fig. 3, the origin of the measurement was the Jianda garden community, and the destination was the school gate. To understand the exposure to traffic-related pollutants on different routes, two representative routes, namely, route A and route B, were selected for the test. Route A is the route on the left side of Fig. 3a; it is approximately 760-m long and passes the main road and crossroads, which have heavy traffic. Route B is the route on the right side of Fig. 3a; it is approximately 742-m long and passes a road and park path in the community. Routes A and B have similar numbers of commuting students, and the students' families live in the community adjacent to the school, so the routes are very short. It should be noted that although the linear distance of route B appears relatively short on the map, route B contains three sets of steps (as shown in Fig. 3c). Thus, the time required to walk along the two routes is similar, as are the students' preferences for routes A and B.

Data collection

The concentration and exposure risk of traffic-related pollutants are higher in winter, while the concentration of other seasonal pollutants is relatively low. The increased rainy weather in the summer is not conducive to the measurements conducted in the present study. Moreover, while the pollutant concentrations in spring and autumn are similar,

Table 1 A review of studies that have evaluated traffic-related pollutants on different routes

Authors	Method	Period	Parameter	Route distance	Transportation mode	People	City
Garcia-Algar et al. (2014)	Measurement	17:00–21:00	UFPs (20–1000 nm)	5 km	Walking	Infants, adults	Barcelona, Spain
Kumar et al. (2017)	Measurement	08:00–09:00; 15:00–16:00	PMC (0.25–32 μm); PNC (0.2–1 μm)	2.7 km	Walking	Infants	Guildford, UK
Elford and Adams (2019)	Simulation (simulated routes and dosage models)		UFPs	< 1.6 km	Walking	Children	Toronto, Canada
Mölter and Lindley (2015)	Simulation (network analysis and GIS)		NO ₂ , PM ₁₀	< 1.5 km	Walking	Children	Manchester, England
Li et al. (2017)	Simulation (GIS and inverse distance weighting) and measurement	07:00–09:00	PM ₁ , PM _{2.5} , PM ₁₀		Motorcycle, bicycle, walking	Commuters	Taipei, China
Ragetti et al. (2014)	Simulation (air pollution models: PROKAS, ESCAPE, PoluMap)		NO ₂		Bicycle, walking	Commuters	Basel, Switzerland
Miao et al. (2015)	Cross-sectional study		Polycyclic aromatic hydrocarbons	≤ 304.8 m	Bus, metro/train, bicycle, foot, motorcycle, truck, car	Commuters	Montreal, Canada
Li et al. (2015)	Measurement	07:00–09:30; 14:00–16:30	BC, PM _{2.5}		Taxi, bus, subway, cycling, walking	Commuters	Shanghai, China
Cole-Hunter et al. (2012)	Measurement	07:00–08:00	PNC, particle diameter		Bicycle	Cyclists	Brisbane, Australia

the concentration of coarse particulate matter may sometimes increase in spring due to sand dust (Li et al. 2019), which is a factor that requires consideration. Jinan has a typical temperate monsoon climate, with high temperature and rain in summer, cold and dry in winter, and four distinct seasons (Zhu et al. 2018). Jinan is from March to May in spring, from June to August in summer, from September to November in autumn, and from December to February (next year) in winter. Ultimately, measurements in winter were carried out in January 2021, while measurements in spring were carried out in April 2021. The test periods were consistent with students' commuting times, namely, from 06:30 to 08:00, and from 15:30 to 17:00. The duration of each test was 10 ± 1 min. To facilitate data processing, each test was numbered. The pollutant concentrations along route A were measured 70 times in 35 rounds, which are respectively numbered as A1–A70. The pollutant concentrations along route B were measured 68 times in 34 rounds, which are respectively numbered as B1–B68. The correspondence between specific test dates and numbers is reported in Table 2. Background data from the monitoring

station were obtained from the China Air Quality Online Monitoring and Analysis Platform (Wang 2013). The background hourly meteorological conditions during the measurement are presented in Fig. 4. In this paper, according to ASHRAE113-2013 standard, draft rate during the test was calculated (ASHRAE 2013), as shown in Fig. 4c. Eighty-nine percent of the test time, students felt draft sensation, but there was no difference in the dissatisfaction of the two routes, which had no influence on students' choice of routes. Moreover, it should be noted that wind speed affects the distribution of particulate matter (Mei et al. 2018), and the average wind speed in the study area in spring is greater than that in winter.

Two multifunctional air quality detectors (CEM DT-9883 M, China) were used to collect particulate matter concentration data on the levels of both PM_{2.5} and PM₁₀. The concentrations of particulate matter concerned are the mass concentration of accumulative counts measured in six channels, with a size range ranging from 0.3 to 10 μm (Fig. 5a). The instrument works according to the principle of light scattering and uses a pump to draw

Fig. 2 The geographic location of the test site: **a** the location of the test site; **b** the position of the test area relative to the nearby background monitoring station

air into the measuring chamber. The air in the measuring chamber generates light pulse signals by scattering light beams, which are then converted into pulse signals related to the number of particles (Adeniran et al. 2017; Goyal and Kumar 2013; Onyango et al. 2019; Srimuruganandam and Shiva Nagendra 2010). Finally, each channel converts the quantity signal into mass concentration signal through the conversion equation. The instrument response time is less than 10 s. The sampling flow rate was 2.83 L/min. The concentrations of $PM_{2.5}$ and PM_{10} were measured within the range of 0–2000 $\mu\text{g}/\text{m}^3$, and the measurement accuracy was 1 $\mu\text{g}/\text{m}^3$. The test interval was 10 s. The instruments were calibrated by the manufacturer prior to the start of measurement for both seasons. Field calibration was performed by weighing the mass of the

polytetrafluoroethylene filter that collected particles during the test and comparing it with the particle mass data generated by the instrument (Adeniran et al. 2017; Kumar and Goel 2016; Pipal et al. 2011). The location of the researchers was recorded once per second using a Global Positioning System (GPS, Zhuolin A8; Fig. 5b). All the instruments were carried by the researchers in backpacks at a height of approximately 1.2 m, which represents the average breathing height of the children. The field measurements were conducted when the students were walking and keeping pace with their walking speed, in order to realistically collect the exposure of particulate matter during the walking commute. Note that the mobile testing method has been extensively used as shown in the Table 1.

Fig. 3 The characteristics of the test routes: **a** map; **b** steps on route A; **c** steps on route B

Table 2 The test dates and test numbers

Season	Date	Morning		Afternoon	
		Route A	Route B	Route A	Route B
Winter	2021 Jan 15	A1–A6	B1–B6	A7–A12	B7–B14
	2021 Jan 20	A13–A18	B15–B22	A19–A24	–
Spring	2021 Apr 07	A25–A30	B23–B28		
	2021 Apr 08			A31–A36	B29–B34
	2021 Apr 12	A37–A42	B35–B40		
	2021 Apr 14	A43–A46	B41–B44		
	2021 Apr 19	A47–A52	B45–B50		
	2021 Apr 21	A53–A58	B51–B56		
	2021 Apr 28			A59–A64	B57–B62
	2021 Apr 29			A65–A70	B63–B68

Exposure assessment

Exposure was assessed using the RDD based on the International Commission on Radiological Protection (ICRP) model (Hinds 1999). The RDD was estimated according to Eq. (1) and is related to the tidal volume (V_T , cm^3), breathing frequency (BF , breaths/second), deposition fraction (DF), and PMC:

$$RRD_{PM(fractions,i)} = V_T \times BF \times DF_i \times PM_i, \quad (1)$$

where the unit of $RDD_{PM(fractions,i)}$ is $\mu\text{g/s}$ and DF_i and PM_i ($\mu\text{g/m}^3$) are the DF and PMC for each of the i -th PM fractions, respectively. Moreover, the DF_i values are calculated based on the mass median diameter (d_p , μm) of the PM in

Fig. 4 The weather conditions and draft rate during the test period: **a** winter; **b** spring; **c** draft rate

Fig. 5 Test instrument: **a** particulate concentration collection instrument; **b** GPS

various size ranges (Azarmi and Kumar 2016) using Eqs. (2) and (3), as given by Hinds (Hinds 1999):

$$DF = IF \left(0.058 + \frac{0.911}{1 + \exp(4.77 + 1.485 \ln d_p)} + \frac{0.943}{\exp(0.508 - 2.58 \ln d_p)} \right), \quad (2)$$

where IF is the inhalable fraction, which is calculated by Eq. (3):

$$IF = 1 - 0.5 \left(1 - \frac{1}{1 + 0.00076 d_p^{2.8}} \right), \quad (3)$$

where d_p is the average particle diameter (μm), which is based on the mass of the coarse and fine particle fractions.

For males (females) during sitting, light exercise, and heavy exercise, V_T is, respectively, equal to 750 (460), 1250 (990), and 1920 (1360) cm^3 per breath (Hinds 1999). For males (females), the value of BF is taken as 0.2 (0.24), 0.34 (0.35), and 0.44 (0.55) during sitting, light exercise, and heavy exercise, respectively (Hinds 1999). The students considered in this study walk to and from school, so their exercise level is light exercise. Therefore, for male (female) students, V_T was considered to be 1250 (990) cm^3 per breath, and BF was considered to be 0.34 (0.35) breath per second.

IBM SPSS software was used to conduct T tests on the data, and $P < 0.05$ indicates statistically significant differences.

Total respiratory deposition dose

Madureira et al. (2020) used the multiple-path particle dosimetry model to quantify the total respiratory deposition of particulate matter in newborns and mothers. Patterson et al. (2014) evaluated cumulative exposure to UFPs by simulating a 24-h school day exposure period using the number of hours children spend in each microenvironment. To further explore the exposure risk of students during their commute, a new parameter index, namely, the TRDD (total respiratory deposition dose), is introduced according to the ICRP model to calculate the total amount of particulate matter inhaled by students during their annual commuting time. TRDD represents the amount of particulate matter inhaled in a certain period, which is determined by RDD and exposure time. The calculation method of the TRDD is given by the following:

$$\text{TRRD}_{PM(\text{fractions})} = \text{RDD}_{PM(\text{fractions})} \times T_e, \quad (4)$$

where RDD_{PM} is calculated by Eq. (1) and T_e is the annual commuting exposure time, min.

TRDD index can improve the risk assessment of traffic-related pollution exposure from a relatively macro-perspective and can uncover the impact of traffic pollution on primary school students during their commute under different

traffic conditions over different years. Thus, it can provide guidance for the commuting arrangement of primary school students on a year or semester basis.

Uncertainty analysis

In order to quantify the accuracy of measurements, an uncertainty analysis of the measured data is carried out based on the General Law of Uncertainty Propagation (ISO. 1995). The uncertainty can be obtained by the following equations (Mathioulakis et al. 1999), and results are listed in Table 3.

$$u_i = \left(\frac{w_i^2}{3} \right)^{0.5} \quad (5)$$

$$U_R = \left(\sum_{i=1}^n u_i^2 \right)^{0.5} = \left(\frac{1}{3} \sum_{i=1}^n w_i^2 \right)^{0.5}$$

where u_i is the standard uncertainty of measured parameter; w_i is the accuracy of device; and U_R is the standard uncertainty of the parameter determined by other measured parameters.

Results

The concentrations of $\text{PM}_{2.5}$ and PM_{10} along different commuting routes around a primary school during different commuting periods were tested in the field and relatively accurate and true pollutant data reflecting the exposure environment of primary school students were obtained. The concentrations of particulate matter on different routes during the test period were analyzed and compared with data from the background monitoring site. The distributions of particulate matter at different locations along different routes can be intuitively observed via the resulting spatial distribution diagrams. To assess the exposure of primary school students, the RDD values under various conditions were calculated, based on which the TRDD during the annual commuting period was calculated.

Particulate matter concentrations during the measurement

Figure 6 presents the concentrations of particulate matter at different times in winter, from which it is evident that the concentrations of particulate matter in winter were always at a high level. During the winter measurement,

Table 3 Accuracy and uncertainty of measured parameters

Parameters	Devices	Accuracy	Uncertainty
$\text{PM}_{2.5}$ concentration	CEM DT-9883 M	$\pm 1 \mu\text{g}/\text{cm}^3$	$0.58 \mu\text{g}/\text{cm}^3$
PM_{10} concentration	CEM DT-9883 M	$\pm 1 \mu\text{g}/\text{cm}^3$	$0.58 \mu\text{g}/\text{cm}^3$

Fig. 6 The comparison of pollutant concentrations at different times in winter: **a** route A; **b** route B

the concentration of $PM_{2.5}$ ranged from 104.8 to 259.6 $\mu\text{g}/\text{m}^3$, while that of PM_{10} ranged from 152.7 to 542.0 $\mu\text{g}/\text{m}^3$. The lowest measured concentrations of $PM_{2.5}$ and PM_{10} all appeared along route B. Along route A, the $PM_{2.5}$ and PM_{10} concentrations in the afternoon in winter were found to be respectively increased by 38.8 and 132.8 $\mu\text{g}/\text{m}^3$ as compared with the concentrations in the morning, and the concentration of coarse particles was 3.4 times that of fine particles. Along route B, the $PM_{2.5}$ and PM_{10} concentrations in the afternoon in winter were found to be respectively increased by 41.3 and 238.3 $\mu\text{g}/\text{m}^3$ as compared with the concentrations in the morning.

As is shown in Fig. 7, the concentration of particulate matter in spring was significantly lower than that in winter. During the spring measurement, the $PM_{2.5}$ concentration ranged from 12.1 to 176.2 $\mu\text{g}/\text{m}^3$, and the PM_{10} concentration ranged from 35.5 to 365.4 $\mu\text{g}/\text{m}^3$. Similar to the winter, the lowest measured concentrations of $PM_{2.5}$ and PM_{10} all appeared along route B. The temporal variation of PMC in spring was not consistent with that in winter. In spring, the average concentrations of $PM_{2.5}$ and PM_{10} on route A in the afternoon were 41.3 and 87.1 $\mu\text{g}/\text{m}^3$ lower than those in the morning, respectively. Moreover, the average concentrations of $PM_{2.5}$ and PM_{10} on route B were 21.9 and 50.6 $\mu\text{g}/\text{m}^3$ lower than those in the morning, respectively, which is related to the climatic characteristics of Jinan in spring.

The average concentrations of particulate matter at different times along different routes, as well as the concentrations collected at the background monitoring station, are reported in Table 4. The results of Shapiro–Wilk Test showed that the data obeyed normal distribution (Shapiro and Francia 1972). *T*-tests were carried out on the measured data during data processing, and the results were found to be statistically significant. According to the data, the particulate

matter concentrations on route A were higher than those on route B in different seasons and at different times. In winter, the concentrations of particulate matter along the two routes were higher than those determined by the background monitoring site, and the highest concentration was 2.94 times the background monitoring value. The $PM_{2.5}$ concentration in winter as determined by the background monitoring station was lower in the afternoon than in the morning, while the background PM_{10} concentration was higher in the afternoon than in the morning, and the measured values were all higher in the afternoon than in the morning. In spring, the measured average concentrations of PM_{10} on routes A and B in the afternoon were respectively 25.4 and 28.3 $\mu\text{g}/\text{m}^3$ lower than the background values. The measured values at other times were still higher than the background values. In the afternoon, students' commuting time is often earlier than the evening rush hour in the city, and the increase in the particulate matter concentration along the traffic routes around the school is not detectable by background monitoring stations.

The ratio of the actual measured particulate concentration to the background data is represented by $C_{a/b}$, and the specific relationship is presented in Fig. 8. In winter, the average concentrations of $PM_{2.5}$ and PM_{10} on route A were 2.4 and 1.8 times higher than those at the background monitoring site, and those on route B were 2.0 and 1.6 times higher than those at the background monitoring site. In spring, the average concentrations of $PM_{2.5}$ and PM_{10} on route A were 1.8 and 1.8 times higher than those at the background monitoring site, and those on route B were 1.4 and 1.4 times higher than those at the background monitoring site. The decrease of the $PM_{2.5}$ concentration in spring is obvious and corresponds to the decrease of traffic flow for picking up and dropping off students in spring (Xiao et al. 2019; Zhao et al. 2019). In winter, the average concentration

Fig. 7 The comparison of pollutant concentrations at different times in spring: **a** route A; **b** route B

of $\text{PM}_{2.5}$ on route A was 1.19 times that on route B in the morning ($P=0.000$) and 1.14 times that on route B in the afternoon ($P=0.012$). Moreover, in winter, the average concentration of PM_{10} on route A was 1.11 times that on route B in the morning ($P=0.001$) and 1.08 times that on route B in the afternoon ($P=0.000$). In spring, the average $\text{PM}_{2.5}$ concentration on route A was 1.3 times that on route B in the morning ($P=0.000$) and 1.02 times that on route B in the afternoon ($P=0.012$). Furthermore, in spring, the average PM_{10} concentration on route A was 1.25 times that on route B in the morning ($P=0.000$) and 1.03 times that on route B in the afternoon ($P=0.012$). By comparison, it

can be determined that the particulate matter concentration on route B was lower than that on route A in both seasons. Thus, choosing a route away from the main road will expose students to lower levels of traffic pollution.

Spatial variation of particulate matter concentrations

To provide a more intuitive comparison of the changes in the concentration of particulate matter along different routes and at different positions on the same route, Figs. 9 and 10 present the cloud maps of the changes in the concentrations of

Table 4 The comparison of the average particulate matter concentrations with the background values

Season	Time	PMC ($\mu\text{g}/\text{m}^3$)	Background				
			Background	Route A	Average Difference	Route B	Average Difference
Winter	Morning	PM _{2.5}	96.3 ± 14.1	197.2 ± 51.1	100.9	166.1 ± 35.0	69.8
		PM ₁₀	194.8 ± 56.2	350.2 ± 56.3	155.4	312.8 ± 61.9	118
	Afternoon	PM _{2.5}	80.3 ± 8.8	236.0 ± 35.2	155.7	207.4 ± 50.0	127.1
		PM ₁₀	277.7 ± 58.4	483.0 ± 52.1	205.3	445.4 ± 57.4	167.7
Spring	Morning	PM _{2.5}	40 ± 15.9	90.0 ± 32.6	50	69.2 ± 14.1	29.2
		PM ₁₀	96.6 ± 22.1	197.7 ± 71	101.1	158.3 ± 60.1	61.7
	Afternoon	PM _{2.5}	40.1 ± 22.1	48.7 ± 12.5	8.6	47.3 ± 9.6	7.2
		PM ₁₀	136 ± 53.4	110.6 ± 47.7	-25.4	107.7 ± 31.4	-28.3

Fig. 8 The ratios of the actual particulate matter concentration to the background concentration ($C_{a/b}$): **a** $\text{PM}_{2.5}$; **b** PM_{10}

particulate matter in different seasons and at different times. For winter, runs A1 and B1 in the morning and runs A7 and B7 in the afternoon were selected. For spring, runs A25 and

B23 in the morning and runs A59 and B57 in the afternoon were chosen. The test periods of these sample routes were the same, and the concentrations of particulate matter were

Fig. 9 The comparison of the pollution status of different routes in winter: **a** $PM_{2.5}$ in the morning (taking A1 as an example); **b** PM_{10} in the morning (taking B1 as an example); **c** $PM_{2.5}$ in the afternoon (taking A7 as an example); **d** PM_{10} in the afternoon (taking B7 as an example)

close to the average levels. Thus, the test environment could represent the daily living environment.

As can be seen from Fig. 9, in winter, the concentrations of $PM_{2.5}$ and PM_{10} on route A were higher than those on route B, which is also proven by the data reported in the “Particulate matter concentrations during the measurement” section. The concentrations of $PM_{2.5}$ and PM_{10} at the entrance of the residential area, i.e., at the traffic lights near the origin, were higher than those at other places. This is because this is the access hub at which vehicles are waiting at idle speed, thereby resulting in sharp increases in the concentrations of particulate matter up to $514 \mu\text{g}/\text{m}^3$ ($PM_{2.5}$) and $629.5 \mu\text{g}/\text{m}^3$ (PM_{10}), which are respectively 4.7 and 251 times the background values. The particulate matter concentrations of the main road section (section A_b) on route A were significantly higher than those at other sections, as is evident from Fig. 9c and d. This is mainly due to the large traffic flow in section A_b and the existence of traffic lights; this leads to vehicle congestion and idle operation, which

causes traffic-related pollutants to gather around the road and spread to the walking area. It takes approximately 5 min for students to walk along this section. According to Eq. (1), in a single trip along this section, students will inhale at least $10 \mu\text{g}$ of $PM_{2.5}$, which will remain in their lungs for at least 3 months (Hinds 1999). This poses a serious threat to the health of the students’ lungs (Peng et al. 2019). Although the concentrations of particulate matter on both routes exceeded the standards, the concentrations of only a few locations on route B exceeded those on route A.

As can be seen from Fig. 10, the concentrations of particulate matter on the two routes in spring were decreased as compared with those in winter, and the low-concentration distribution area along the entire route was significantly higher in spring than in winter. However, increased pollutant concentrations caused by congestion at the gate of the community were still found to exist. As compared to that in winter, the proportional area with high concentrations of pollutants in section A_b decreased in spring, which was

Fig. 10 The comparison of the pollution status of different routes in spring: **a** PM_{2.5} in the morning (taking A25 as an example); **b** PM₁₀ in the morning (taking B23 as an example); **c** PM_{2.5} in the afternoon (taking A59 as an example); **d** PM₁₀ in the afternoon (taking B57 as an example)

due to the obvious decrease of traffic flow in spring and the decrease in the number of idle vehicles on the road. Furthermore, the existence of breezes during the spring measurements was also a reason for the reduction of the accumulation of particles.

In sections A_c and A_d, the concentrations of particulate matter exceeded those in section A_b on the main road (Fig. 10d, Figs. SI 1a and SI 1d, Fig. SI 3). This is because sections A_c and A_d are located in a building complex, and the airflow in the street canyon is hindered; this causes the short-term accumulation of particulate matter at the leeward side, resulting in the increase of pollutant concentrations. As shown in Figs. 10c and d, at the intersection of the end points of routes A and B, the concentrations of particulate matter were found to suddenly increase, which was caused by the indoor stairwell. Some dust accumulated in the stairwell, and when the number of pedestrians increased, the amount of dust increased. However, when the students stayed in the stairwell for less than 1 min, the maximum amount of PM_{2.5}

inhaled during this time was less than 4 µg, which was less than the amount of PM_{2.5} inhaled in the section with the highest pollutant concentration on route A (10 µg). The dust control measurement of staircases is relatively easy to achieve, and as shown in Fig. SI 3, after simple sprinkling measures were taken, the points of high particulate matter concentrations disappeared. In general, route B has fewer areas with high particulate matter concentrations, and the overall exposure risk is less than that of route A.

Exposure assessment

The RDD is adapted from the ICRP model; it represents the amount of particulate matter inhaled by the respiratory system and is widely used in the assessment of inhaled doses of pollutants. It is suitable for the analysis of particles with uniform particle size and does not require the calculation of the specific deposition area. Figure 11 first compares the RDD of PM_{2.5} ($RDD_{PM2.5}$) of male and female students in different

Fig. 11 The comparison of the $RDD_{PM_{2.5}}$ values of males and females under different exercise states

exercise states, taking the average $PM_{2.5}$ concentration of run A1 as an example. The selection of the relevant parameters was explained in the “Total respiratory deposition dose” section. It can be seen from the figure that the $RDD_{PM_{2.5}}$ value of males is higher than that of females in the three exercise states, but the proportion is different. The students considered in this study walk to school, which is considered light exercise. In the following analysis, the RDD values of males are taken as an example by default (Kumar et al. 2017), and the RDD values of females can be calculated as the RDD values of males divided by 1.2.

As shown in Figs. 12 and 13, in winter, the $RDD_{PM_{2.5}}$ and $RDD_{PM_{10}}$ values on route A in the morning were, respectively, 2.4–3.4 and 6.3–9.8 $\mu\text{g}/\text{min}$; in the afternoon, these values were, respectively, 3.2–3.8 and 10.2–12.6 $\mu\text{g}/\text{min}$. On route B in winter, the $RDD_{PM_{2.5}}$ and $RDD_{PM_{10}}$ values in the morning were, respectively, 1.6–3.0 and 3.5–9.5 $\mu\text{g}/\text{min}$; in the afternoon, these values were, respectively, 2.7–3.5 and 9.7–11.4 $\mu\text{g}/\text{min}$. In winter, while the variation range of the RDD values on route A was greater than that on route B in the morning, the opposite relationship was found in the afternoon.

In spring, the $RDD_{PM_{2.5}}$ and $RDD_{PM_{10}}$ values on route A were, respectively, 0.7–2.6 and 2.9–8.5 $\mu\text{g}/\text{min}$; in the afternoon, these values were, respectively, 0.3–1.8 and 1.2–4.8 $\mu\text{g}/\text{min}$. On route B in spring, the $RDD_{PM_{2.5}}$ and $RDD_{PM_{10}}$ values in the morning were, respectively, 0.5–1.4 and 2.8–6.3 $\mu\text{g}/\text{min}$; in the afternoon, these values were, respectively, 0.2–1.6 and 0.99–4.4 $\mu\text{g}/\text{min}$, respectively. Compared with those in winter, the variation ranges of the RDD values were found to be increased in spring. In spring, the $RDD_{PM_{2.5}}$ values of the two routes in the afternoon were similar, indicating that the effect of traffic on the increase of the $PM_{2.5}$ concentration was less than that of wind during the commuting time in the afternoon.

On average, as shown in Fig. 14a, in winter, the $RDD_{PM_{2.5}}$ and $RDD_{PM_{10}}$ values on route A in the morning were, respectively, 0.5 and 1.1 $\mu\text{g}/\text{min}$ higher than those on route B, and in the afternoon, the values were, respectively, 0.4 and 0.7 $\mu\text{g}/\text{min}$ higher. The advantage of route B is more obvious in the morning in winter; by comparing the RDD values of the two routes in different seasons, it is evident that the RDD values on route B were always lower than those on route A, which indicates that route B is more suitable for students to walk.

As shown in Fig. 15, the $RDD_{PM_{2.5}}$ was taken as an example to show the students’ $PM_{2.5}$ respiratory deposition dose at the background particulate concentration and measured particulate concentration, and corresponding to the wind velocity during the test. The overall respiratory deposition dose included the effects of ambient particulate matter and current traffic-related particulate matter, both of which were affected by weather to some extent. According to the calculation results of background monitoring station data, it can be seen that the respiratory deposition dose caused by background particulate pollution was less than the overall respiratory deposition dose in most of the time, especially in winter.

It should also be noted that the concentration of background particulate matter in winter was a great threat to students’ health, while traffic activities greatly increased the exposure risk of students during commuting time. The effect of wind speed on particulate distribution was worth considering as an important parameter. For the tests conducted on the same day, it is found that when wind speed increased in spring, particulate concentration and exposure risk decreased. When the wind speed was low in winter, the alleviating effect of severe pollution was not obvious.

Analysis of total respiratory deposition dose

According to the actual measurement process, it takes approximately 11 min to complete either route A or B. The numbers of school days in 2018 and 2019 were counted, and due to the impact of COVID-19, the planned number of school days in 2020 was considered. The concentrations of background particulate matter used for calculation and the actual school days are shown in SI 5. The concentrations of $PM_{2.5}$ and PM_{10} required in this part of the calculation were determined by backward extrapolation from the relationship between the measured data and the background data reported in the “Particulate matter concentrations during the measurement” section. In winter, the ratios of the mean concentrations of particulate matter on route A to the background concentration were 2.36 ($PM_{2.5}$, $P=0.000$) and 1.83 (PM_{10} , $P=0.000$). Moreover, in winter, the ratios of the mean concentrations of particulate matter on route B to the background concentration were 2.03 ($PM_{2.5}$, $P=0.000$) and

Fig. 12 The comparison of the $RDD_{PM2.5}$ values in different seasons, at different times, and on different routes: **a** morning; **b** afternoon

1.62 (PM_{10} , $P=0.000$). In spring, the ratios of the average concentrations of particulate matter on route A to the background concentration were 1.76 ($PM_{2.5}$, $P=0.000$) and 1.80 (PM_{10} , $P=0.000$). Furthermore, in spring, the ratios of the

average concentrations of particulate matter on route B to the background concentration were 1.40 ($PM_{2.5}$, $P=0.008$) and 1.44 (PM_{10} , $P=0.018$). The ratios to the background concentrations in autumn and summer were calculated via

Fig. 13 The comparison of the RDD_{PM10} values in different seasons, at different times, and along different routes: **a** morning; **b** afternoon

the average values in winter and spring, and the results are reported in Table 5.

According to the calculation results, the average annual amounts of $PM_{2.5}$ and PM_{10} inhalation in 3 years on route A were respectively found to be 7018 and 19,660 μg , and those on route B were respectively 5874 and 16,543.5 μg . The

amount of particulate matter inhaled on route A was found to be significantly higher than that on route B. The difference between the two routes was 1144 μg , which accounted for 16.3% of the inhalation on route A. It is evident that in the long run, the selection of route B will greatly reduce $PM_{2.5}$ inhalation. Due to the impact of COVID-19 in 2020, the traffic

Fig. 14 The variation range of the RDD on routes A and B in different seasons: **a** winter; **b** spring

Fig. 15 The variation range of the RDD_{PM2.5} and corresponding wind velocity in different seasons and backgrounds: **a** winter; **b** spring

Table 5 The annual inhalation of particulate matter during commuting from 2018 to 2020

Year	PM	Route A (μg)	Route B (μg)	Difference (μg)
2018	PM _{2.5}	6854	5736	1118
	PM ₁₀	19430	16378	3052
2019	PM _{2.5}	7446	6234	1212
	PM ₁₀	21090	17744	3346
2020	PM _{2.5}	6326	5292	1034
	PM ₁₀	17030	14308	2722
Mean	PM _{2.5}	7018	5874	1144
	PM ₁₀	19660	16543.5	3116.5

flow in the most recent half a year was lower than that in the previous 2 years (Zhou et al. 2022). The comparison of the inhalation of PM_{2.5} and PM₁₀ over 3 years showed that the average amounts of PM_{2.5} and PM₁₀ inhalation in 2020 were respectively 11.1% and 14.7% lower than those in the previous 2 years, which proves the contribution of traffic to the increase of particulate matter concentrations.

Discussion

The research object of this study was the commuting route of students in a primary school in Jinan, China. The selected school is a classic and traditional public primary school, and its commuting mode and surrounding traffic situation can therefore represent most primary schools in Jinan. The seasons selected in this study were winter and spring, as these seasons have relatively high concentrations of traffic-related pollutants. In addition, the rainy weather in summer and long summer holidays were not conducive to the measurement conducted in the present study. Due to the significance of the seasonal variations in pollutant concentrations due to climate change, climate should be taken into account when developing mitigation measures. It should be noted that nitrogen oxides are also traffic-related pollutants, but they were not analyzed in this paper, because this paper focused on the impact of particulate matter on students' respiratory system and calculated the respiratory deposition dose. The impact of nitrogen oxides on students' health mainly damaged students' cognitive and developmental nervous system (An et al. 2021; Sunyer et al. 2017).

Particulate matter concentrations during the measurement

While vehicle exhaust has a greater impact on the concentration of fine particulate matter (Nagpure et al. 2016; Yang et al. 2020; Yuan et al. 2013), the data collected in the present study indicate that the increase of coarse particulate matter was greater than that of fine particulate matter, which was not only caused by traffic exhaust. Due to the morning weather conditions in winter that the air relative humidity in the study area was high, the particulate matter could not be easily re-suspended under the influence of vehicles and human activities. As the temperature increased in the afternoon, the air relative humidity decreased, and particles were more likely to be re-suspended by the surrounding activity. As a result, the concentrations of particulate matter were higher in the afternoon than that in the morning in winter.

During the morning rush hour in spring, the airflow in the street canyon was relatively stable, and it was difficult for the particulate matter caused by traffic to dilute smoothly. The afternoon weather was often breezy, and the movement of the air carried out the pollutants that had accumulated in the street canyons. However, when the wind speed was too high, the amount of dust increased, resulting in the increase in the concentrations of particulate matter, as shown in A34–A36 and B32–B34 in Fig. 7. The limits of the specific wind speed require further exploration.

Limitation of the test

The increase in particulate matter concentrations caused by traffic includes two aspects, namely, direct emissions and dust resuspension (Harrison et al. 2012; Sinogaya and Manatad 2020). The resuspension of dust on roads makes it impossible to clearly distinguish the proportion of particulate matter concentration increases caused by traffic emissions, making it difficult to determine the impact of traffic exhaust emissions alone. From the perspective of students' health, regardless of the cause, elevated concentrations of particulate matter will threaten students' health. Dust sprinklers and decorative tree hedgerows are now widely used to alleviate dust exposure (Amini et al. 2016).

Previous studies have shown that the variation of the RDD between different commuting modes is often greater than the variation of the same commuting mode over the course of a day (Kumar et al. 2018). This study only considered the exposure risk of commuting on foot, and did not compare it with other commuting methods because most students in the study area commute on foot. In addition, this study focused on the necessity of choosing a low-risk route by comparing the exposure status and exposure risk between different routes under the same commuting mode.

Limitation of background monitor station

The data monitored by the background station reflect the concentrations of particulate matter at a certain height in a certain area, which can only reflect the air pollution situation over a wide range. It is evident from the large gap between the background concentration and the measured data, as well as the difference in the time distribution, that it is difficult for the background monitoring data to accurately represent the traffic pollution situation around the selected school during commuting, and it is not sufficiently objective to determine the actual traffic pollution exposure of students. Therefore, it is more advantageous to perfect traffic pollution monitoring systems, increase the number of monitoring points, and reduce the monitoring range.

Mitigation measures

The selection of route B was found to reduce students' particulate exposure by up to 22%. Ignoring the effect of commuter routes can lead to a significant attenuation bias of 4% (95% confidence interval: 4–5%) (An et al. 2021; Ragettli et al. 2015). To reduce the exposure of students to traffic pollutants during the daily commute to and from school, schools and neighborhoods should encourage students to walk to school.

Trees and hedges can interrupt the transmission of traffic-related pollutants. Vertical greening can effectively reduce

PM_{2.5} concentration when road width is unchanged. Continuous planting of single rows of saplings leads to 17% reduction in PM_{2.5} levels (Ozdemir 2019). Meanwhile, urban greening can improve lung health among students in low-to-medium pollution areas (Zhou et al. 2021). Therefore, it is necessary to plant trees and hedges along the road.

It is also feasible to use pollutant filters to reduce the concentration of pollutants in the environment. Placing filters in areas with high pollutant concentrations (such as traffic hotspots) can reduce PM₁₀ concentration by at least 4.1% (Bächler et al. 2021). In terms of pollution control, it is an important measure to eliminate vehicles with large emissions and encourage citizens to buy new energy vehicles. Parents could avoid idling when picking up and dropping off students, which can effectively reduce the concentration of particulate matter.

Conclusion

This study compared the exposure of primary school students to particulate matter on different commuting routes during commuting periods through the field measurements, and the following conclusions were drawn. In winter and spring, the concentrations of PM_{2.5} and PM₁₀ on route A (high-traffic route that is near the main road) were greater than those on route B (low-traffic route that is off the main road), with respective averages of 1.2- and 1.1-fold increases. The average annual amount of PM_{2.5} inhalation on route B over 3 years was found to be 16.3% lower than that on route A. Therefore, the selection of route B will significantly reduce the amount of PM_{2.5} inhaled by commuting students.

Traffic activity exacerbates pollution with particulate concentrations. When the background particulate concentration is high, the wind velocity has little effect on the alleviation of particulate concentration in the environment. When the background particulate concentration is low in spring, the wind velocity can reduce the particulate concentration on the commuting route to some extent. To reduce exposure to traffic-related pollution, there will often be a lower-dose route. According to the characteristics of route B, it is necessary to choose a commuter route that is far away from the main road and to avoid traffic intersections and traffic lights; thus, roads within communities are better choices for student commuters.

Nomenclature BC: Black carbon; RDD: Respiratory deposition dose (μg/min); TRDD: Total respiratory deposition dose (μg/min); UFPs: Ultrafine particles; PM: Particulate matter; PMC: Particulate matter concentration (μg/m³); PNC: Particulate matter number; ICRP: International Commission on Radiological Protection; V_T: Tidal volume (cm³); BF: Breathing frequency (breaths/second);

DF: Deposition fraction; IF: Inhalable fraction; d_p : Average particle diameter; T_e : Annual commuting exposure time

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Author contribution Farun An collected the data, analyzed the data, and wrote the original draft. Jiying Liu provided the research concepts and methodology and reviewed and edited the manuscript. Wanpeng Lu and Daranee Jareemit reviewed and edited the article. All authors read and approved the final manuscript.

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Ethics Committee (represented by Science and Technology Department) of Shandong Jianzhu University. Verbal consents were obtained from participants.

Consent for publication The authors are giving their consent for this study to be published in the journal of Environment Science Pollution Research.

Competing interests The authors declare no competing interests.

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